



Pressure Transducer Performance and Measurement Trade-Offs in a Transient, High Temperature, Combustion Environment

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13. ABSTRACT (Maximum 200 words) At the U.S. Army Research Laboratory (ARL), a series of tests were performed in a 120-mm cannon to characterize the effects of transducer type, transducer port configuration, thermal protection media, and severe mechanical forces on the amplitude and frequency response of the pressure measurement. A ring of five pressure transducer ports (72° apart) was machined 2.6 m from the rear face of a 120-mm gun tube. The physical configuration of the transducer ports consisted of three single-diameter ports with varying stand-off distances, a conventional two-diameter port, and blind port. As the projectile passed the longitudinal position the pressure transducers were exposed to a transient, high temperature environment which allowed the investigators to study the fidelity of the pressure measurement under transient, high temperature, mechanically adverse gun conditions. These tests demonstrated that the use of single-diameter pressure ports with cavity depths of 0.254 mm (0.010 in) and 0.711 mm (0.028 in) will more accurately characterize the oscillatory nature of the pressure measurement than would the use of a single-diameter port with a cavity depth of 1.600 mm (0.063 in). In addition, the combustion chamber of the weapon was also highly instrumented with pressure transducers in an attempt to evaluate the effects of various transducer types and thermal protection greases on the magnitude of the pressure measurement. This study showed that the Kistler 6211 pressure transducer (quartz) reads about 5% higher than the E30MA pressure transducer (tourmaline) in both the forward and rear of the chamber. No conclusion could be reached as to which gage gives the more correct quasi-steady-state pressure level.				
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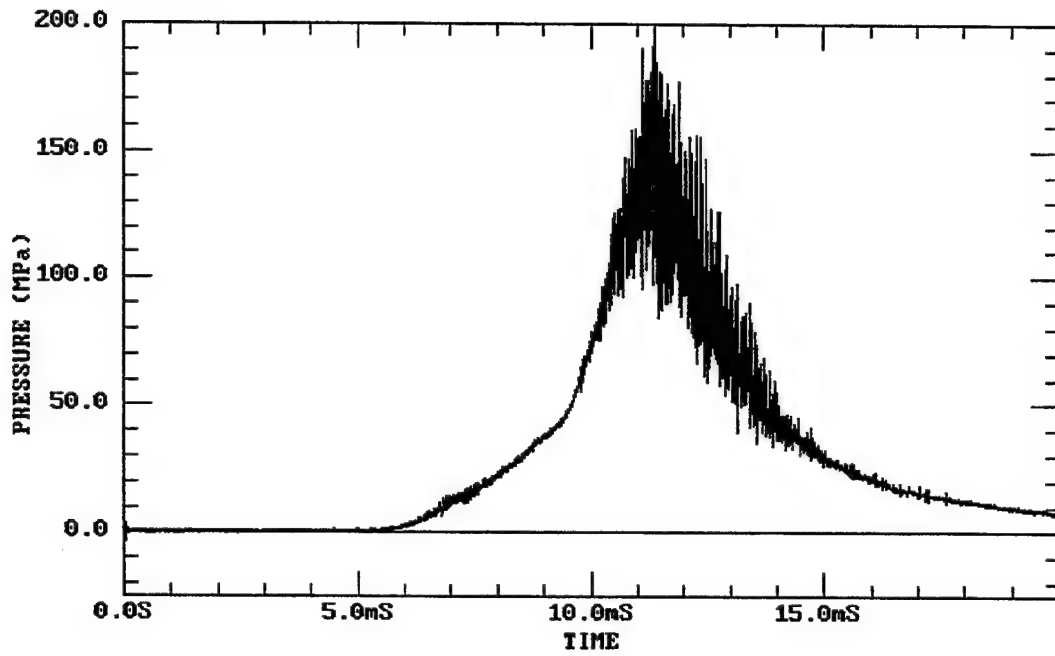
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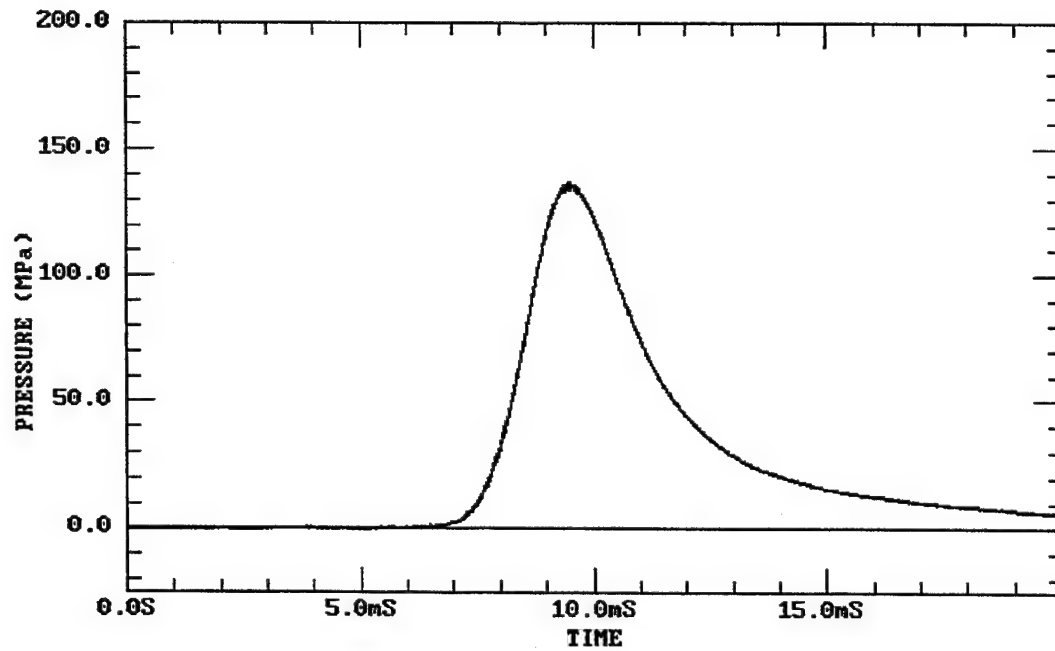
1.0 INTRODUCTION

With the emergence of advanced propulsion systems such as liquid propellant, electrothermal-chemical, conventional hypervelocity, and inbore ramjet, the measurement of combustion phenomena has become more complex. The data associated with these systems can be rich in high-frequency components and share similar transient behavior. Figure 1 shows a pressure versus time (p-t) plot of the combustion chamber pressure of a regenerative liquid propellant gun (RLPG) and a conventional solid propellant gun, respectively. The difference in these two p-t histories is obvious. The RLPG p-t plot exhibits high-frequency pressure fluctuations that can be as high as 100 kHz.¹ Conversely, the solid propellant p-t history exhibits a much lower frequency spectrum - typically less than 5 kHz. Though the RLPG data are presented here as an example, they are not unique in their frequency content. Several of the propulsion technologies mentioned also exhibit similar high-frequency characteristics.

It has been demonstrated that the pressure measurement techniques associated with the characterization of the quasi-steady-state, or mean pressure, of conventional solid propellant combustion phenomena are adequate to characterize the mean pressure in the RLPG. However, this technique is not adequate to accurately characterize the high-frequency oscillatory portion of the RLPG combustion process, as noted by the pressure transducer manufacturers.²⁻³ Consequently, the accuracy of pressure and acceleration measurements in combustion chambers, barrels, and onboard projectiles has been compromised. The measurement inadequacies were caused by the lack of a fundamental understanding of the effects of the mounting configuration and the mechanical and electrical components of the transducer on the integrity of the measurement, and the disregard for the transducer manufacturer recommendations for mounting transducers to acquire high-fidelity data.²⁻³ Current combustion chamber, gun tube, and onboard projectile measurements required to characterize the response of system components to these highly-transient, spectrally-rich combustion environments may be inadequate. Subsequently, the technical understanding of the physical processes involved in the ignition and combustion of such advanced propulsion systems and, therefore, their development, may be compromised.



(a)



(b)

Figure 1. (a) Regenerative Liquid Propellant Gun Combustion Chamber Pressure-Time History and (b) Conventional Solid Propellant Gun Combustion Chamber Pressure-Time History.

2.0 INTERIOR BALLISTIC PRESSURE MEASUREMENT METHODOLOGY

The techniques used to calibrate ballistic pressure transducers and to measure interior ballistic combustion pressure in conventional solid propellant guns and simulators are generally well known and accepted.^{2-3,12-13} Many researchers make use of piezoelectric pressure transducers mounted in standard two-diameter pressure transducer ports to quantify the combustion pressure. Thermal protective material is used to protect the transducer from the very high temperature combustion environment. This procedure has been well documented and is considered reliable for quantifying combustion phenomena with a relatively low-frequency spectra ($< 5\text{kHz}$). However, the data associated with some advanced propulsion systems can be rich in high-frequency components. Consequently, there are two distinct parts of the pressure measurement that must be considered: the quasi-steady-state portion and the oscillatory portion. The technique just described is adequate to characterize the quasi-steady-state portion of the combustion pressure, but severely biases the oscillatory portion due to frequency limitations imposed by the transducer-mounting technique.

In 1992 Dr. G.A. Benedetti of Sandia National Laboratories (SNL) put forward both a theoretical and experimental explanation of this phenomenon.⁴ To make a good measurement, the system requires a flat response ($P_{\text{out}}/P_{\text{in}}=1$) over the frequency range of interest associated with the input signal. This implies that the natural frequency of the gage port cavity and the transducer must be significantly higher than the highest frequency of interest in the input signal (i.e., $f_{\text{natural cavity}} \geq 5 f_{\text{input signal}}$).

Figure 2 shows the steady-state pressure response spectrum for a two-diameter gage cavity (shown in Figure 3). In the figure, ω is the frequency of pressure oscillation at the gun tube wall and ω_n is the first undamped natural circular frequency for the cavity. As one can see, at about 20% of the resonant frequency, the magnitude of $P_{\text{out}}/P_{\text{in}}$ begins to be amplified. At frequencies near the resonant frequency, the input signal will be severely amplified. At frequencies significantly higher than the natural frequency, the input signal will be severely attenuated. As one would expect, this would have a profound effect on the fidelity of the data if the resonant frequency of the transducer cavity is low with respect to the range of input frequencies of interest. Given the relatively low first natural frequency of a standard two-diameter pressure transducer port filled with grease or hot combustion gas (f_n about 40 kHz assuming speed of sound is about 1000 m/s),⁵ there is no doubt that the frequency content of such high-frequency pressure data are biased above 8 kHz. Experimental data put forward by the ARL also verified this phenomenon.⁶

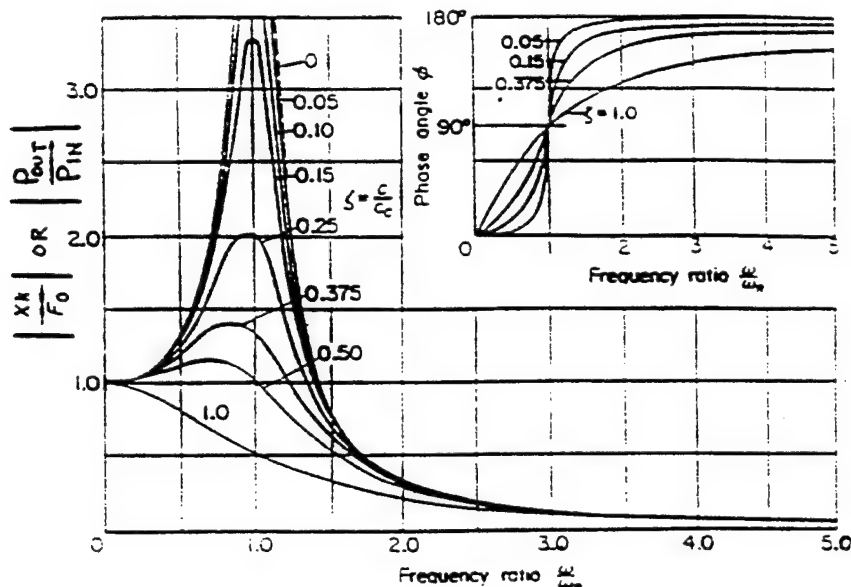


Figure 2. Steady-State Pressure Response Spectrum for a Two-Diameter Gage Cavity.

During a 1993 JANNAF Combustion Subcommittee Workshop entitled "Measurement Techniques in Highly-transient, Spectrally-rich Combustion Environments," a procedure to accurately resolve both the quasi-steady-state and the oscillatory portion of the spectrally rich data was put forward and agreed to by representatives of the gun propulsion instrumentation community.⁶ The recommended procedure is outlined in Figure 3.

Recommended procedure to be used for studying high-frequency oscillations:

- * Use both two-diameter ports with grease and one-diameter ports without grease
- * Use low-pass filtered pressure-time history from two-diameter port to define the "quasi-steady-state," or mean pressure
- * Use pressure-time history from the one-diameter port, with mean pressure (and likely thermal drift effects) removed, to define the oscillatory pressure



Two-diameter Port

- Quasi-steady-state (mean) pressure
- 2.286 mm (0.090 in) offset
- Mechanically stable transducer
- Grease for thermal protection



One-diameter Port

- Oscillatory pressure
- ≤ 0.762 mm (0.030 in) offset
- Well characterized transducer
- No grease (likely extreme thermal drift)

Figure 3. Recommended Procedure to Be Implemented When Characterizing Both the Quasi-Steady-State and Oscillatory Portions of a Spectrally Rich Combustion

This procedure is intended to alleviate the frequency response limitations of the standard pressure transducer mounting technique. However, it requires the experimentalist to take at least two pressure measurements in order to accurately characterize both the mean pressure and the oscillatory pressure. Implementation of this procedure has improved the quality of the data, but more research must be completed to determine if there are any additional effects associated with the highly transient, spectrally rich combustion environments on the integrity of interior ballistic pressure measurements. To this end, the ARL initiated a program to investigate several fundamental issues yet unresolved by the measurement community. The objective of this program was to characterize the effects of transducer type, transducer port configuration, thermal protection medium, and severe mechanical forces on the amplitude and frequency content of the pressure measurement.

3. EXPERIMENTAL SETUP

A substantial amount of work has been done to evaluate the integrity and response of various pressure transducers in shock tubes.⁷⁻⁸ These tests have generally lacked the severe thermal and mechanical conditions actually present in the interior ballistic environment. At the ARL, a series of tests were performed in a 120-mm cannon to characterize the effects of transducer type, transducer port configuration, thermal protection medium, and severe mechanical forces on the amplitude and frequency response of the pressure measurement. All pressure measurements at locations other than the 2.6-m down-bore location were taken with Kistler 6211⁹ and E30MA¹⁰ transducers. Pressure measurements taken in the 2.6-m down-bore position were made using primarily Kistler 607C4² piezoelectric pressure transducers. The Kistler 6211 and the E30MA were used in this study because they are currently under evaluation for ballistic pressure measurements at ARL and ATC.⁸ Conversely, the 607C4 pressure transducer was evaluated because of its use in the 30-mm RLPG program at the ARL. Alternate pressure transducers and filling materials were used in some of the tests and will be specifically noted as discussed. In every case, the data were recorded using a data acquisition system with a digitization rate of 1 MHz per channel. Table 1 outlines the pressure transducer locations in the chamber as well as down the tube. All measurements were taken from the rear face of the tube, and the angular positions are determined from a frame of reference looking down range with a counter clockwise rotation.

Table 1. Pressure Transducer Locations

Transducer Designation	Axial Location	Angular Location
	cm (in)	(degrees)
P1L	9.5 (3.75)	40
P1R	9.5 (3.75)	300
P3L	48.9 (19.25)	60
P3R	49.9 (19.25)	350
P7	229.2 (90.25)	330
P100	254.3 (100.13)	0
PA	260.4 (102.50)	0
PB	260.4 (102.50)	288
PC	260.4 (102.50)	216
PD	260.4 (102.50)	144
PE	260.4 (102.50)	72
P8	305.4 (120.25)	30

Of special importance is the ring of five pressure transducer ports (72° apart, denoted PA-PE) that were machined 2.6 m from the rear face of the gun tube. The physical configuration of the transducer ports at this location consisted of three single-diameter ports with varying stand-off distances (dimension l_p), a conventional two-diameter port, and a blind port (shielded from the gas pressure by 0.66 cm (0.260 in) of steel). All five of these pressure ports were specified to be machined for a Kistler 607C4 pressure transducer. Figure 4(a) shows the configuration of the single diameter ports (PA-PC) and 4(b) shows the configuration for the two-diameter port (PE). Figure 4(c) shows the actual dimensions and the theoretical cavity natural frequencies calculated from the following equations.²

Two-diameter cavity natural frequency:

$$f_n = \frac{C_o}{2\pi} \sqrt{\frac{A_p}{V_c l_p}} ; \quad \text{where } A_p = \frac{\pi d_p^2}{4}$$

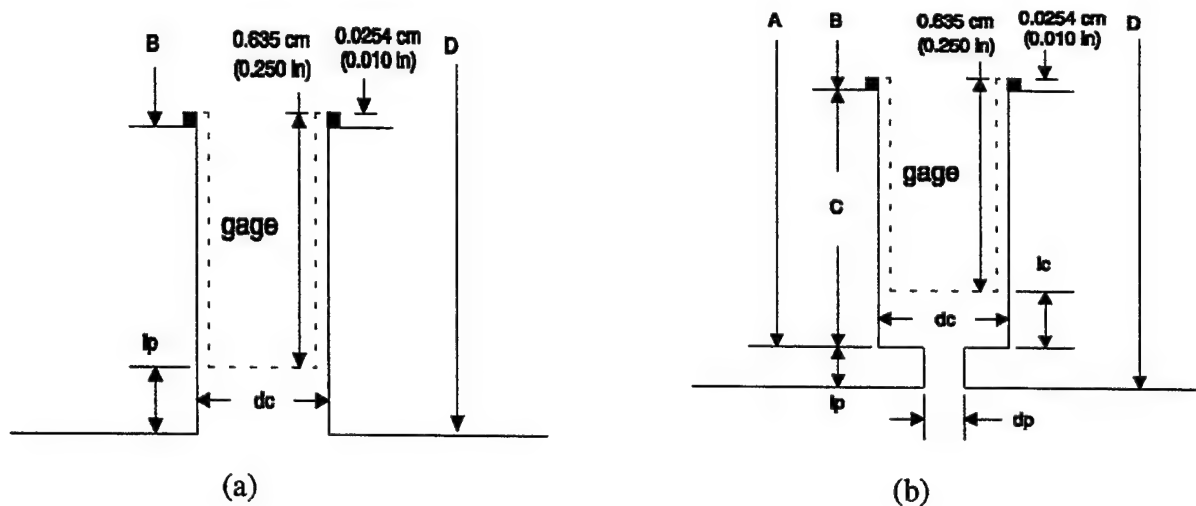
$$V_c = \frac{\pi d_c^2 l_c}{4} + \frac{\pi (d_c^2 - 0.635) l_g}{4} \quad \text{and } l_g = C + 0.010 - l_c$$

* C_o is the speed of sound in the cavity (approximately 330 m/s in air, 1,000 m/s in combustion gas, and 5,000 m/s in grease)

Single-diameter cavity natural frequency:

$$f_n = \frac{C_o}{4l_p} ;$$

The equation used for the natural frequency of the single-diameter ports is the equation for the natural frequency of a pipe closed at one end. It is acknowledged that this equation may not hold for a pipe with a very small length to diameter ratio (L/D) such as in this case. However, since there is no known experimental data to either support or refute the applicability of this equation, it is viewed as a reasonable first approximation to the natural frequency of the single-diameter gage cavity.



Gage	Conf.	A	B	C	D	l_c	l_p	d_p	d_c	f_n
		cm (in)	cm (in)	cm (in)	cm (in)	cm (in)	cm (in)	cm (in)	cm (in)	(kHz)
PA	1-Dia.	N/A	3.792 (1.493)	N/A	4.427 (1.743)	N/A	0.025 (.010)	N/A	0.635 (0.250)	955
PB	1-Dia.	N/A	3.752 (1.477)	N/A	4.432 (1.745)	N/A	0.071 (0.028)	N/A	0.638 (0.251)	341
PC	1-Dia.	N/A	3.658 (1.440)	N/A	4.427 (1.743)	N/A	0.160 (0.063)	N/A	0.636 (0.2505)	152
PD	Blind	N/A	3.137 (1.235)	N/A	4.427 (1.743)	N/A	0.660 (0.260)	N/A	0.638 (0.251)	N/A
PE	2-Dia.	4.201 (1.654)	3.600 (1.417)	0.602 (0.237)	4.425 (1.742)	0.018 (0.007)*	0.224 (0.088)	0.160 (0.063)	0.640 (0.252)	38.1

$C_0 = 97,500 \text{ cm/sec}$ ($38,400 \text{ in/sec}$) for these calculations

*two seals used due to machining error.

(c)

Figure 4. (a) Configuration of Single-Diameter Pressure Ports (PA, PB, PC), and (b) Configuration of Two-Diameter Pressure Port (PE), and (c) Dimensions and Natural Frequencies of Associated Pressure Transducer Cavities.

As the projectile passed the longitudinal position 2.6 m down tube, the pressure transducers (PA-PE) were exposed to a transient, high-temperature environment. This impulse allowed the investigators to study the fidelity of the resultant pressure measurement taken under transient, high-temperature, mechanically adverse gun conditions. Strain measurements were also taken at this location in an attempt to correlate the incidence of the shock wave traveling in the barrel to the incidence of the gas pressure wave behind the projectile. In addition, the combustion chamber of the weapon was highly instrumented with pressure transducers in an attempt to evaluate the effects of various transducer types and thermal protection greases on the magnitude of the chamber pressure. A 15-GHz microwave interferometer was used to determine projectile displacement and subsequent velocity at any time during the interior ballistic cycle.¹⁰

Since identical interior ballistic performance was desired, a well-characterized charge and a projectile (Figure 5) were used. The charge was designed to achieve a pressure level of 400 MPa in the combustion chamber and 200 MPa at 2.6 m down the bore using a propellant with a flame temperature of 3,400 K. The projectile was chosen because it has been well characterized and makes use of a standard obturator for the fielded 120-mm weapons system. A narrower obturator band configuration would have been more desirable to allow a more abrupt uncovering of the gage ports down tube. However, the time and cost associated with designing and testing a new obturator for this projectile would have gone beyond the scope of this research. As will be shown in the experimental data, the band proved to cause an interesting dynamic effect on the transducers, while still producing the desired step function.

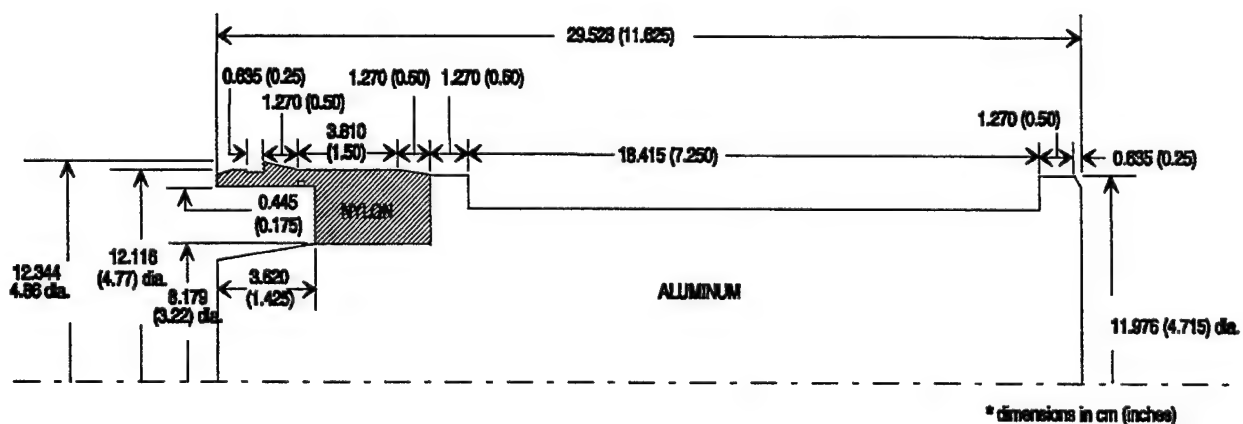


Figure 5. 120-mm Test Projectile.

Sixteen rounds were fired with the same charge and projectile weight, thus producing nearly identical interior ballistic performance in all cases (projectile velocity at 2.6 m nominally 1260 m/s). After each test, every transducer was removed from its respective gage port. Both the gage and the gage port were thoroughly cleaned, new grease was placed on the face of the gage (when used), and the gage was retorqued to the manufacturer's specifications. The manufacturer's torque specifications were 20 ft-lb force for the Kistler 607C4s, PCB 119M43s, and the E30MAs; and 7 ft-lb force for the Kistler 6211s. Steel seals specified by the manufacturers were used in each case.

4.0 RESULTS AND DISCUSSION

4.1 Effects of Obturator Configuration on the Pressure Measurement. The first step in analyzing the pressure data for subtleties due to pressure port configuration, thermal protection media, and mechanical stimulus is to make sure that the location of the projectile during the interior ballistic cycle is well known. This information is used to more accurately interpret, and subsequently explain, any subtleties observed in the experimental data.

A 15-GHz microwave interferometer was used to determine the location of the projectile as it travelled down the gun tube. Each cycle of the interferometer signal is equivalent to 1.00409 cm of projectile travel. Figure 6 shows a plot of the interferometer signal and the combustion chamber pressure. As the pressure in the chamber increases, the projectile begins to accelerate and, subsequently, the frequency of the interferometer signal increases. If one counts the cycles of interferometer data from onset of projectile motion, the projectile location can be determined at any point in time. Consequently, the position of the projectile with respect to the down bore pressure transducers can be accurately determined.

Figure 7 shows a comparison of the microwave interferometer data and the down bore pressure transducers PA, PB, and PC. If one counts the interferometer cycles from the onset of projectile motion until the small perturbation (precursor wave at the face of the projectile) in pressure noted as point A in Figure 7, one will find that the projectile has moved 177.7 cm. Before firing, the distance from the front of the projectile to the ring of pressure ports (PA-PE) is actually 178.3 cm. The microwave interferometer data correlates the projectile location to the actual measured distance within 0.5 cm. This error can easily be explained through measuring errors, or more likely errors associated with choosing the start of projectile motion, which can be

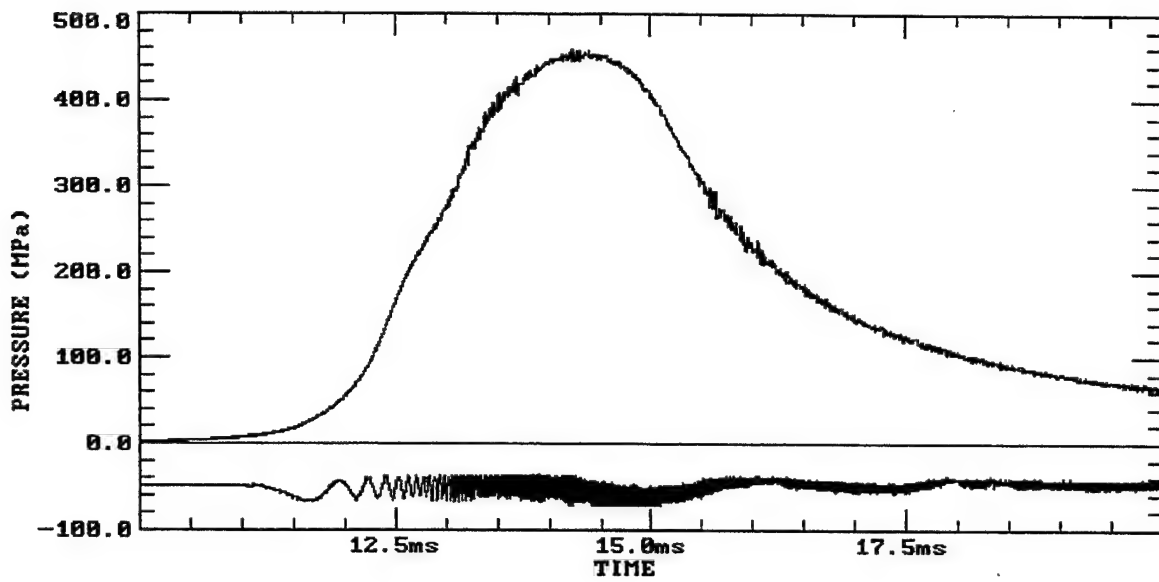


Figure 6. Microwave Interferometer and Combustion Chamber P-t Histories for Round 10.

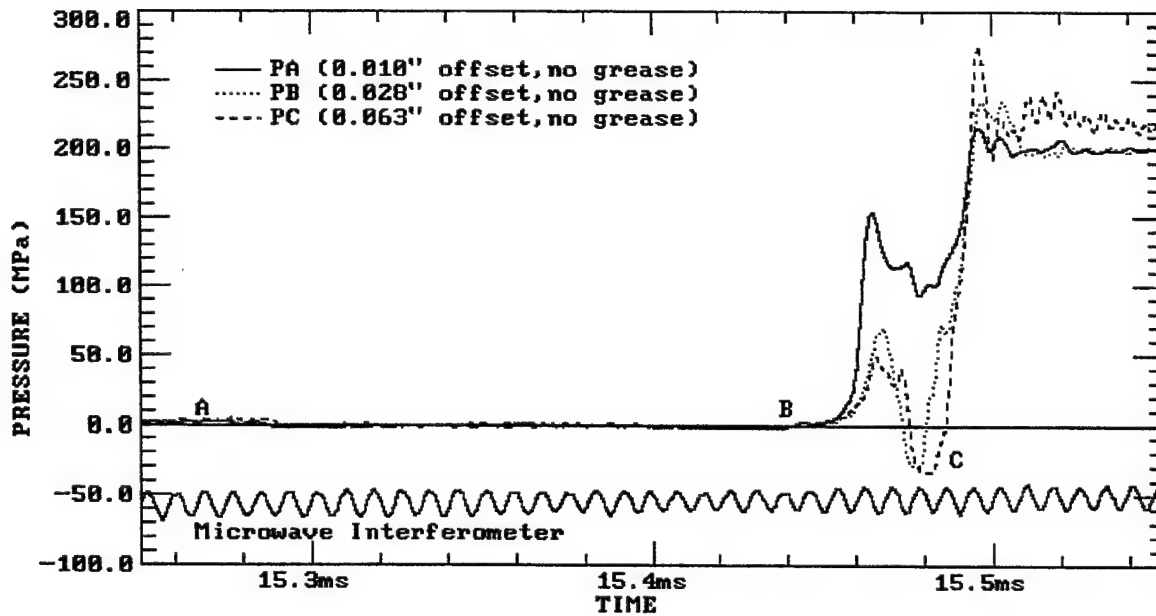


Figure 7. Microwave Interferometer and Down-Barrel P-t Histories for Round 10.

To meet the objectives of this series of tests, the perfect obturator would have provided a condition under which the transducers were covered by the obturator until the projectile passed the transducer's location. At this time the transducers would be exposed to a gas pressure step function. By looking at the down bore pressures PA, PB, and PC in Figure 7 (Round 10, no thermal protection), it is very obvious that this was not the case in these tests. In fact, there was a definite pressurization of all three gages at 15.44 ms and then pressure was partially relieved before all three gages responded simultaneously. This is the case for all 16 rounds fired.

It is important that the physical processes occurring during this time are well understood before any observations concerning any subtle differences in the three measuring systems can be made. There are approximately 21.5 cycles of interferometer data from the passage of the front of the projectile (point A in Figure 7) to the start of pressure rise on PA, PB, and PC (point B in Figure 7). This correlates to 21.59 cm (8.5 in). By inspecting the drawing of the projectile shown in Figure 5, it is clear that the nylon obturator would begin to pressurize the transducer at 21.59 cm (8.5 in) from the front of the projectile. It is important to note the location of the transducers PA, PB, and PC with respect to the obturator diameter. The diameter of a 120-mm gun tube is 12 cm (4.724 in). The distance that the transducers are offset from the combustion gas [lp in Figure 4(a)] is 0.0254 cm (0.010 in), 0.0711 cm (0.028 in), and 0.160 cm (0.063 in), for PA, PB, and PC, respectively. This means that the nylon band could actually pressurize the transducers PA and PB since they are within the outside diameter of the obturator; and, conceivably, PC since it is within 0.0483 cm (0.019 in) of the outside diameter of the nylon band. The data presented in Figure 7 support this assertion. In addition, it appears that the three transducers begin to simultaneously rise about 26.5 cycles from the passage of the projectile front (15.483 ms, point C in Figure 7), which corresponds to 26.62 cm (10.48 in) from the front of the projectile. Referring once again to Figure 5, it is approximately 26.67 cm (10.5 in) from the front of the projectile to the groove on the inside of the nylon obturator. Based on this information, it appears that the obturator band broke at the location of the groove on the inside surface of the band.

The analysis of the other shots in the series demonstrate similar simultaneous rise of pressure at about 26.62 cm (10.5 in) from the front of the precursor. Figure 8 shows the microwave interferometer, PA, PB, and PC, respectively, for Round 14. This round had exactly the same instrumentation as Round 10, except for the pressure transducer used in position PB was a PCB119M43 instead of a Kistler 607C4. The data from this round also demonstrates the

assertions that the nylon band actually pressurized the single-diameter transducer ports and that the obturator band broke at the location of the groove on the inside surface of the band. Though the nylon pressurization varies slightly from shot to shot (presumably because of machining differences in the obturator band and small perturbations in ballistics), the basic assertions of nylon pressurization and a nearly simultaneous rise to a quasi-steady-state pressure level are consistent on PA, PB, and PC on each of the 16 tests. Based on the fact that the data demonstrated that the transducers responded to the gas pressure in a consistent manner after being pressurized by the nylon obturator, it is postulated that the overshoot and oscillatory fluctuation that occurs at peak pressure can be analyzed as if a perfect obturator were used, subsequently exposing the transducers to a pure gas pressure step function.

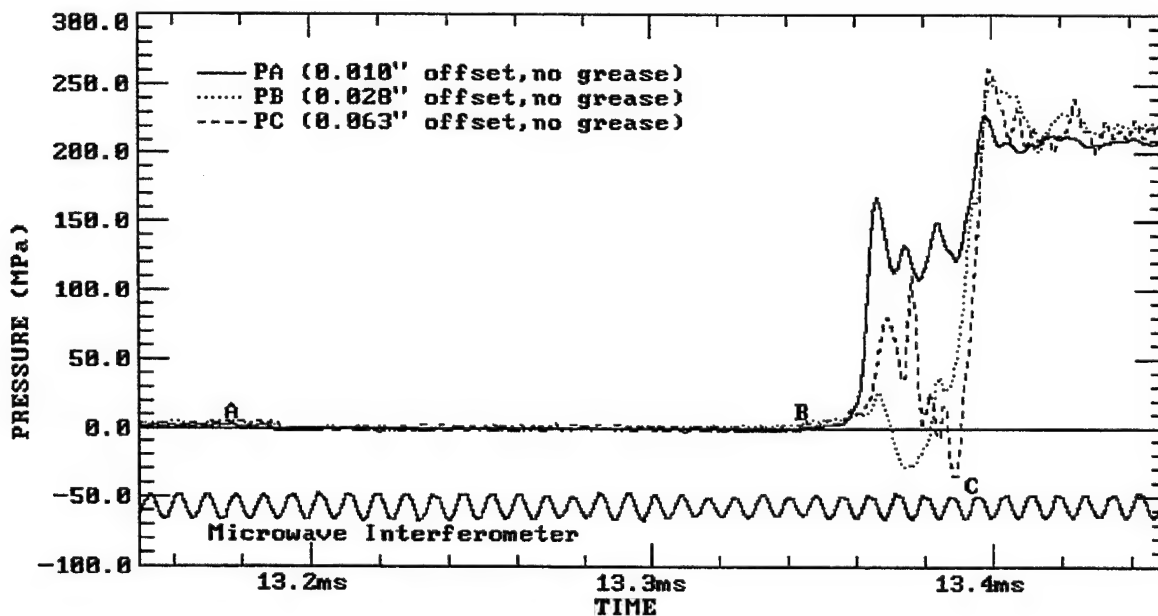
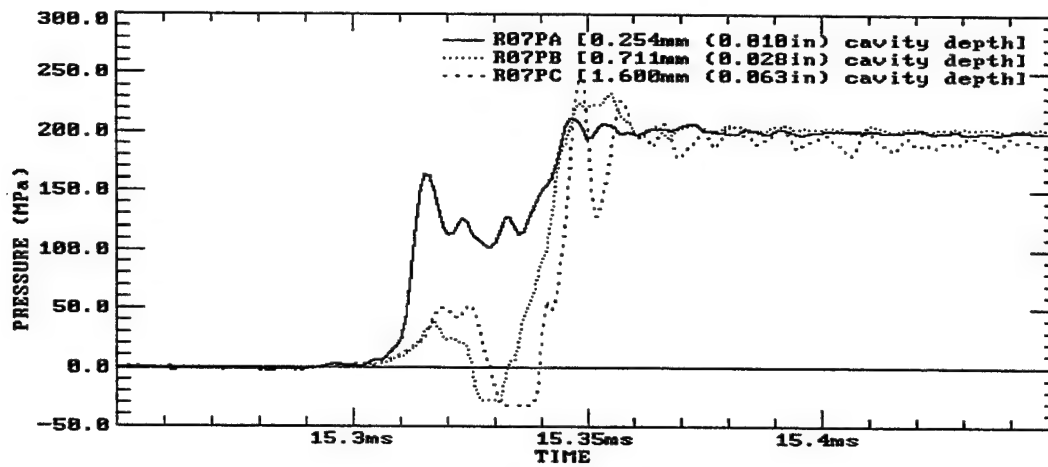
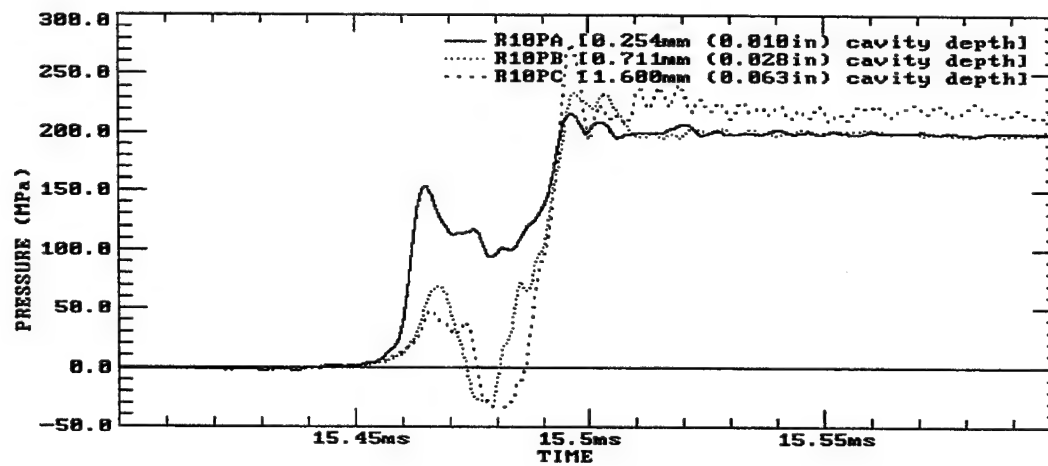


Figure 8. Microwave Interferometer and Down-Barrel P-t Histories for Round 14.

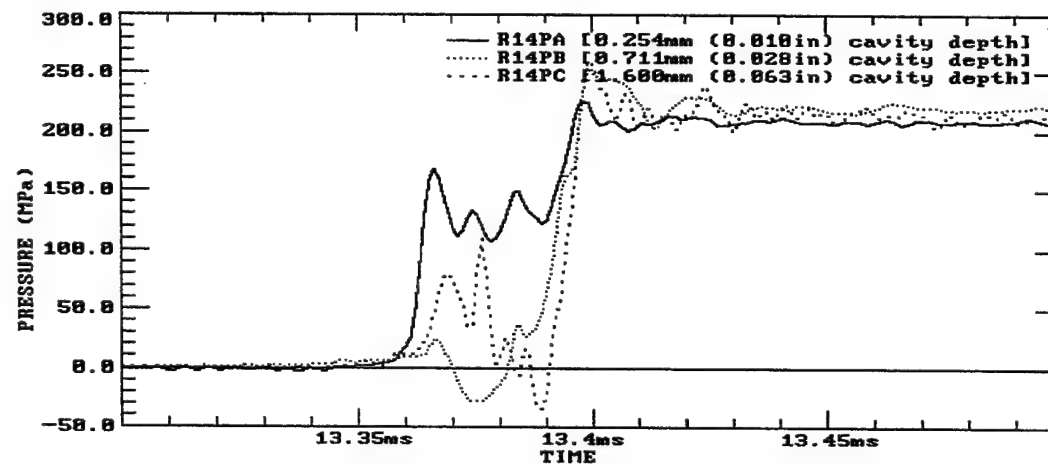
4.2 Effects of Pressure Port Cavity Depth on the Pressure Measurement. As noted earlier, the pressure measurement community has agreed that the use of conventional two-diameter pressure ports limit the frequency response of the measurement to 6-8 kHz. In addition, it was recommended that single-diameter ports with a cavity depth 0.762 mm (0.030 in) or less be used to characterize the oscillatory portion of the pressure measurement.^{2-3,6} To date, no known experimental gun data has been put forward that compares the validity of pressure measurements taken when varying depths of single-diameter pressure port cavities are used. A portion of the 120-mm test plan was dedicated to studying the effects of pressure port cavity depth on the integrity of the pressure measurement.



(a)



(b)



(c)

Figure 9. Down-Barrel P-t Histories for Single-Diameter Pressure Ports With Varying Cavity Depth for (a) Round 7, (b) Round 10, and (c) Round 14.

Based on the conclusion made earlier in this report, the remainder of this analysis will assume that the measuring system would respond in a similar manner to measurements taken in a shock tube environment. That is to say that there would be a very high rate of pressurization with an expectation of overshoot and ringing based on the configuration and components of the measurement system. In addition, the assumption is made that the "hand picked" (based on in-house calibration) Kistler 607C4 pressure transducers used in this test will respond consistently from one shot to the next, and from one transducer to the next. Consequently, it is assumed that any differences exhibited in the pressure-time data could be attributed to the response of the pressure transducer cavity (acoustic cavity).

Of the 16 rounds fired, 4 were fired without grease in the PA, PB, and PC pressure ports. However, results from Round 1 could not be correlated to the known projectile travel profile and, consequently, the data will not be used in this analysis. Therefore, data from the single-diameter pressure port positions from Rounds 7, 10, and 14 will be analyzed and are shown in Figure 9.

In each of the three tests, the pressure rises and falls due to the nylon obturator band, and then rises very quickly as the projectile moves past the pressure transducers. PA [0.254 mm (0.010 in) cavity depth] and PB [0.711 mm (0.028 in) cavity depth] exhibit very similar levels of "ringing and overshoot" after the initial peak pressure is reached. Conversely, PC [1.600 mm (0.063 in) cavity depth] qualitatively exhibits a significantly higher level of ringing than either PA or PB. In an effort to quantify the data from rounds 7, 10, and 14, ringing was defined as the oscillation of the data about a given quasi-steady-state level just after peak pressure. The value of maximum ringing was taken from the plot after the overshoot was complete. This was typically on the second cycle after the high pressure peak, or the maximum peak-to-peak deviation over the first few cycles thereafter; whichever was greater. The percentage values for ringing outlined in Table 2 were arrived at by dividing the peak-to-peak level of ringing by the quasi-steady-state level for each channel.

Table 2. Ratio of Magnitude of Ringing to Quasi-Steady State Pressure Expressed as a Percentage.

Test Number and Pressure Port Configuration	Ratio of Magnitude of Ringing to Quasi-Steady State (expressed as a percentage)
R07PA (1-diameter, 0.254 mm cavity depth)	4.1 %
R10PA (1-diameter, 0.254 mm cavity depth)	3.0 %
R14PA (1-diameter, 0.254 mm cavity depth)	3.0 %
Average for PA	3.3 %
R07PB (1-diameter, 0.711 mm cavity depth)	4.5 %
R10PB (1-diameter, 0.711 mm cavity depth)	1.7 %
R14PB (1-diameter, 0.711 mm cavity depth)	4.0 %
Average for PB	3.4 %
R07PC (1-diameter, 1.600 mm cavity depth)	15.6 %
R10PC (1-diameter, 1.600 mm cavity depth)	8.3 %
R14PC (1-diameter, 1.600 mm cavity depth)	8.9 %
Average for PC	10.9 %

As can be seen from the table, the port with the 1.600 mm cavity depth exhibits an average level of ringing on the order of 11 % of the quasi-steady-state pressure level. On the other hand, the ports with the 0.254-mm and 0.711-mm cavity depths exhibit ringing on the order of 3.5 % of the quasi-steady-state pressure level.

It is important to compare these values to the mechanical vibration/noise experienced by the blind gage, PD, located at the same longitudinal position in the tube. Figure 10 shows a plot of the blind gage for Round 14. If we calculate the percentage of ringing for the blind gage with respect to the quasi-steady-state level of pressure in the tube at the same time as the ringing on the single-diameter pressure port data, the result is 2-3 %. It is reasonable to state that the single-diameter ports with cavity depths of 0.254 mm and 0.711 mm exhibit approximately the same amount of ringing as the blind gage. The origin of the oscillation is not known; however, it is believed to be linked to mechanical vibrations in the gun tube wall and or transducer/transducer cavity.

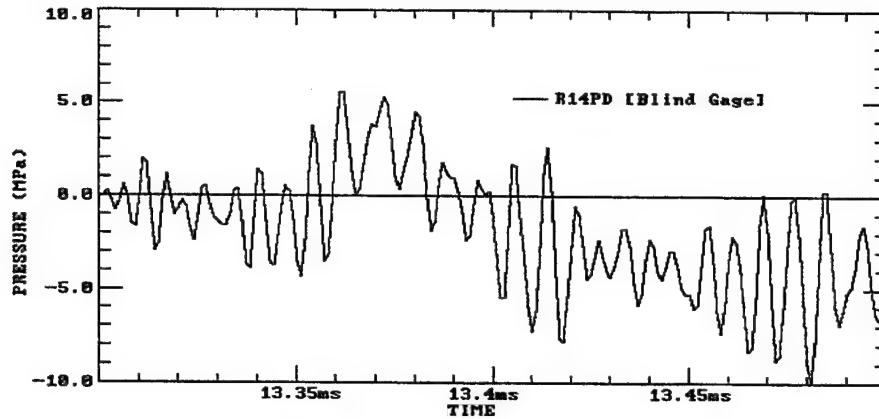


Figure 10. Round 14 Blind Gage (Shielded From Combustion Gases).

It is also interesting to note the general trend in the overshoot seen in most of the tests. As the cavity depth gets larger, the overshoot increased for the same input. In fact, PA and PB do not really exhibit large overshoot and ringing that is normally associated with an acoustical cavity. They tend to reach a peak and very quickly come to oscillate around a quasi-steady-state value with a nominally constant amplitude. On the contrary, PC tends to reach a somewhat higher peak and then, in some cases, exhibits the damped oscillation behavior normally associated with an acoustical resonance, before oscillating around a quasi-steady-state value with nominally constant amplitude.

Recall that a measuring system is flat to approximately 20% of its natural frequency. As the frequency of the input signal approaches the natural frequency of the cavity, the signal would be severely amplified. At frequencies significantly higher than the natural frequency of the cavity, the signal would be attenuated. The increase in peak amplitude would be expected as the cavity depth gets larger and, subsequently, the cavity natural frequency gets smaller, because as the input wave form approaches the natural cavity frequency, the resulting output from the measuring system would be to amplify the signal. This could possibly explain the increase in overshoot with increasing cavity depth. This may suggest that somewhere between a cavity depth of 0.711 mm and 1.600 mm, there is a transition region where the cavity depth begins to play a more important role in the frequency response of the measurement system. In other words, we begin to move from a "pancake" cavity where L/D is not so critical to the frequency response, to an "organ pipe" cavity where the cavity depth begins to play a much greater role in determining the frequency response of the system.

These data do not appear to yield much information concerning the application of the organ pipe equation. They do, however, support the theory that as the depth of the single-diameter cavity gets larger, the natural frequency of the cavity gets lower (not necessarily in proportion to $C_0/4l$). Based on this analysis, which is consistent with the agreement reached at the 1993 JANNAF Combustion Workshop,⁶ the use of single-diameter ports with cavity depths of 0.254 mm and 0.711 mm will more accurately characterize the oscillatory nature of the pressure measurement than would the use of a single-diameter port with a cavity depth of 1.600 mm.

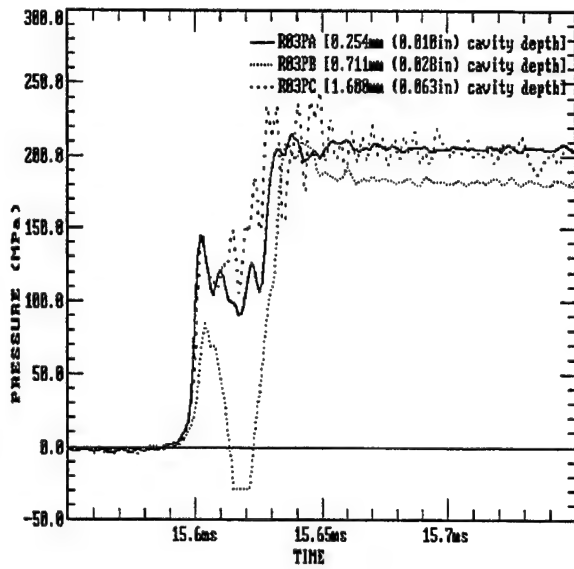
4.3 Effects of Thermal Protective Filling Material on the Pressure Measurement. Traditional pressure measurements have made use of materials such as grease and RTV to limit thermal effects on the pressure transducer. The measurement community has not fully characterized the effects of such gage port filling materials on the fidelity of pressure measurement. One of the major problems associated with the use of grease is the issue of keeping the grease in the gage port during the entire ballistic event. The initial condition before the shot is that the grease is packed into the gage cavity. However, after the test, the grease is no longer in the cavity. It is not known when the grease leaves the cavity. As noted earlier, the frequency response of the cavity is directly proportional to the speed of sound in the cavity. If the grease leaves the cavity during the event, the speed of sound would most likely change, which would have a profound effect on the frequency response of the measuring system. Therefore, it has been recommended by the measurement community⁶ that when frequency response above 6-8 kHz is desired, single-diameter ports with cavity depths of 0.762 mm (0.030 in) or less and no filling material should be used. It was also recommended that more basic research be done to evaluate the effects of thermal protective filling materials.

To this end, another portion of the 120-mm test plan was designed to evaluate the effects of different greases on the pressure measurements. The same instrumentation setup described earlier in this report was used with the exception that a filling material was put in PC [1.600 mm (0.063 in) cavity depth]. Rounds 3, 6, 9, and 12 were completed with no filling material in PA or PB, and a different filling material in PC for each test. A summary of the filling material used for each of these four rounds is presented in Table 3. In each case, the transducer was removed, grease was placed on the face of the transducer, and the transducer was reinstalled in the tube wall.

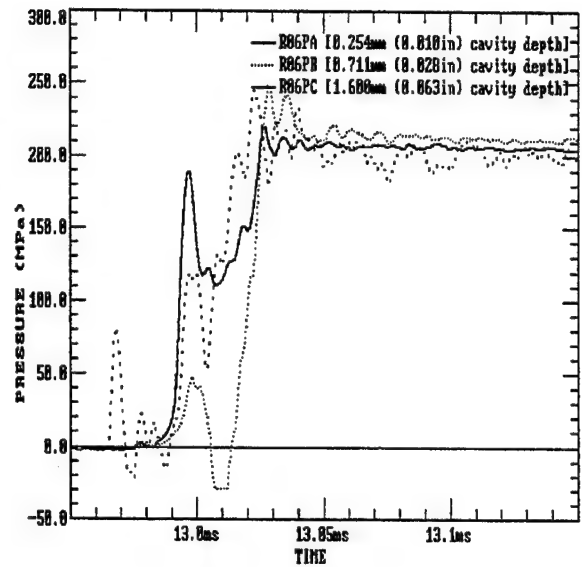
Table 3. Filling Materials.

Test Number and Port Configuration	Filling Material
R03PC (single-diameter, 1.600 mm cavity depth)	(1) Dow Corning high vacuum grease-silicon based
R06PC (single-diameter, 1.600 mm cavity depth)	(2) Wolf's Head #2917 grease-lithium based NLGI #2
R09PC (single-diameter, 1.600 mm cavity depth)	(3) Pennzoil #705 multipurpose lubricant
R12PC (single-diameter, 1.600 mm cavity depth)	(4) Nonfluid Oil Corp. ZL2 multipurpose grease-lithium based NLGI #2

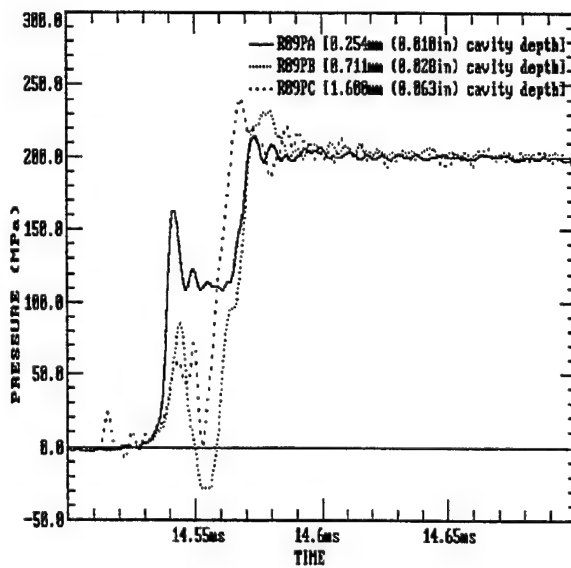
The pressure-time data for Rounds 3, 6, 9, and 12 are presented in Figure 11. In each of the four rounds, the filling material had a profound effect on the pressure measurement. During the event that was earlier assumed to be solid phase impact of the obturator on the diaphragm of the transducer, the PC pressure responds at the same time, or later than PA. The variation in the rise rate of PC during this time could possibly be explained by the different properties of the filling materials, since that is the only difference between Rounds 3, 6, 9, and 12. However, PC reaches peak pressure up to 5 μ sec before both PA and PB once the projectile has passed and the gas pressure can get to the diaphragm of the transducers. Theoretically, the speed of sound in the filling materials will be on the order of five times higher than that of air. It is very hard to estimate this increase because the exact conditions in the cavity, and the response of the filling material under those conditions, are unknown. However, a factor of 5 increase in the speed of sound of the filling material would only increase the response of the transducer by 0.3 μ sec (cavity depth divided by speed of sound in cavity; $0.0016 \text{ m} \div 5,000 \text{ m/s} = 0.32 \text{ } \mu\text{sec}$). Obviously, this does not explain the difference of 5 μ sec between PC with, and without, filling material.



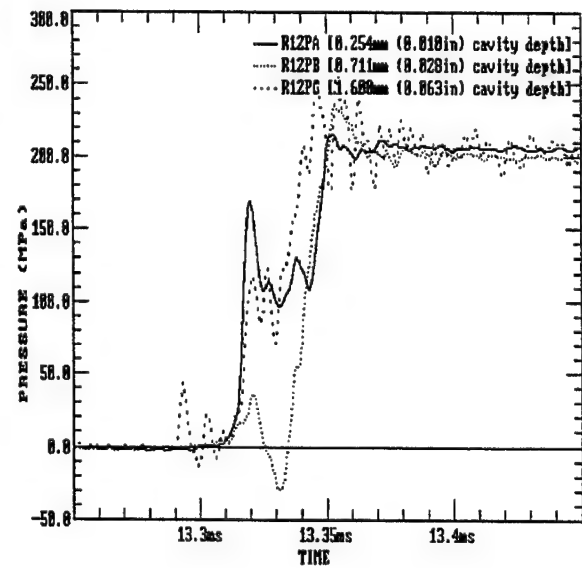
(a)



(b)



(c)



(d)

Figure 11. Down-Barrel P-t Histories for Single-Diameter Pressure Ports With Varying Cavity Depth and Cavity Filling Material in PC for (a) Round 3, (b) Round 6, (c) Round 9, and (d) Round 12.

One possible explanation can be found when we look at the strain data taken on the outside of the gun tube wall at the same longitudinal position as the pressure measurements. Figure 12 shows pressure-time data for PA, PB, and PC on the same plot as the strain. As can be seen in the figure, the strain responds much earlier to the dynamic event than the pressure gages. There is some pressure fluctuation on PC just before all three pressure gages respond together. This fluctuation can be seen on PC in nearly all tests in which filling material was used (See Figure 11) and, conversely, does not show up on PC when no filling material is used (See Figure 9). It may be possible that the dynamic strain wave is coupling through the filling material causing an earlier rise in PC. At this time, this theory is only conjecture and its validity is unsubstantiated. However, a modeling effort is underway to attempt to further study this phenomenon. The other problem that complicates the issue, is the fact that we know the filling material leaves the port sometime during the event. Based on this data, it would appear that the filling material left the cavity sometime after peak pressure due to the consistent early rise of PC for all filling materials. At a minimum, this data shows that filling material has a profound effect on the pressure measurement and appears to cause an earlier pressure rise than can be supported by projectile location determined by the microwave interferometer data.

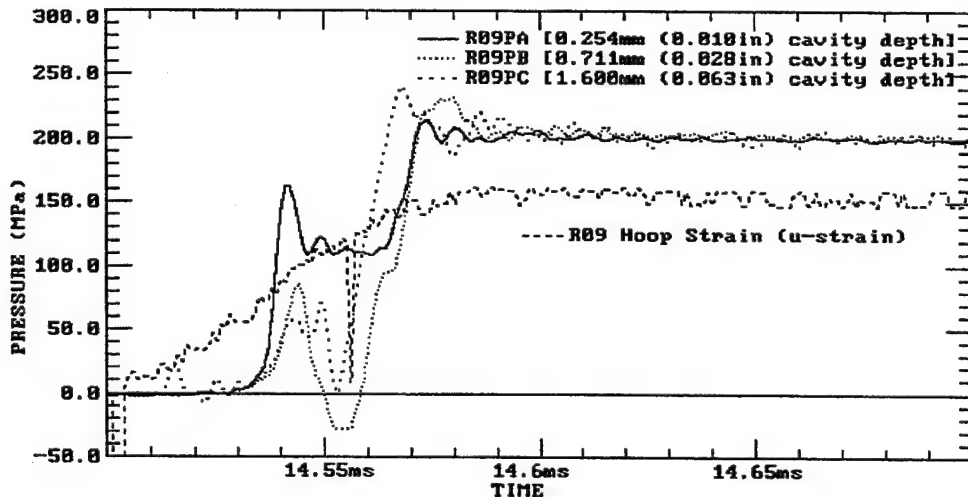


Figure 12. Down-Barrel P-t Data and Hoop Strain for Round 9.

It is also important to look at the effect of the filling material on the issue of ringing after peak pressure on PC. Figure 11 shows quite clearly that the pressure-time data for PC in all four rounds exhibits more oscillatory behavior than PA and PB. Table 4 shows a quantitative comparison of the percentage of ringing for the four rounds where filling materials were used. When compared to the quantitative analysis outlined in Table 2 for the same experimental setup (except there was no filling material in PC), the results are very similar. There does not appear

to be any appreciable change in the amplitude of ringing when filling material is used. Based on the data presented in Figure 11, it is not possible to draw any conclusions concerning the effects due to the differences in the the filling materials. It is important to note that the Kistler 607C pressure transducers that were exposed to the very high temperature combustion environment survived quite well. During testing, only one gage had to be replaced and that was due to a bad sealing surface on the gage. After firing, all the gages were re-calibrated and demonstrated good linearity and repeatability.¹²⁻¹³

Table 4. Ratio of Magnitude of Ringing to Quasi-Steady-State Pressure Expressed as a Percentage for Rounds With Filling Material in Pressure Port Cavity PC

Test Number and Pressure Port Configuration	Ratio of Magnitude of Ringing to Quasi-Steady-State (expressed as a percentage)
R03PA (1-diameter, 0.254 mm cavity depth)	2.9
R06PA (1-diameter, 0.254 mm cavity depth)	2.6
R09PA (1-diameter, 0.254 mm cavity depth)	1.9
R12PA (1-diameter, 0.254 mm cavity depth)	3.2
Average for PA	2.7
R03PB (1-diameter, 0.711 mm cavity depth)	2.6
R06PB (1-diameter, 0.711 mm cavity depth)	3.3
R09PB (1-diameter, 0.711 mm cavity depth)	3.4
R12PB (1-diameter, 0.711 mm cavity depth)	4.4
Average for PB	3.4
R03PC (1-diameter, 1.600 mm cavity depth)	10.4
R06PC (1-diameter, 1.600 mm cavity depth)	12.4
R09PC (1-diameter, 1.600 mm cavity depth)	8.6
R12PC (1-diameter, 1.600 mm cavity depth)	12.6
Average for PC	11.0

4.4 Effects of Thermal Protective Filling Material on the Chamber Pressure Measurement. The measurement of the quasi-steady-state pressure in the combustion chamber of large-caliber guns has become a routine practice. The accuracy of these measurements is important to charge design, propellant lot comparisons, and weapon fatigue testing. Over the past few decades, researchers have discovered inconsistencies in pressure measurements when different types of pressure transducers and different types of thermal protective filling materials were used.¹⁴⁻¹⁷ To study this problem, a portion of the study was designed to determine the effects of different thermal protective filling materials and different transducers on the fidelity of the quasi-steady-state combustion chamber pressure measurement.

Four pressure measurements were taken in the combustion chamber of the 120-mm gun. Table 1 outlines the longitudinal and angular location of pressure P1L, P1R, P3L, and P3R. As noted in the table, P1L and P1R are in the rear of the chamber at the same longitudinal position. P3L and P3R are located in the forward portion of the chamber at the same longitudinal position.

The objective of the first portion of this test was to establish a baseline for the chamber pressure measurements using the standard pressure measurement system used at the Range 18 Large Caliber Test Facility of the ARL. Kistler 6211 piezoelectric pressure transducers and Dow Corning high vacuum silicone grease (as the thermal protection) was used in each of the four chamber locations. The gages were removed between each test. Both the gage and the gage port were cleaned, and grease was placed on the end of each gage. The gages were then re-torqued to the manufacturer's specifications. In addition, the combustible case of the round was drilled in the location of the pressure gages to allow the combustion gases to more easily reach the diaphragm of the respective gage.

Figure 13 shows a representative pressure-time plot for the four chamber pressure measurements in Round 2. Note that the quasi-steady-state level of P1L and P1R, as well as the level of P3L and P3R, nearly overlay when looking at the plot. Table 5 shows the results of the three shot baseline series using 6211 gages and the Dow Corning high vacuum silicone grease. The results of this series demonstrates that the quasi-steady-state pressure level in the chamber agree within about 1%. This also implies that the gage calibration, gage linearity, mounting torque repeatability, and measurement process are good to about 1%.

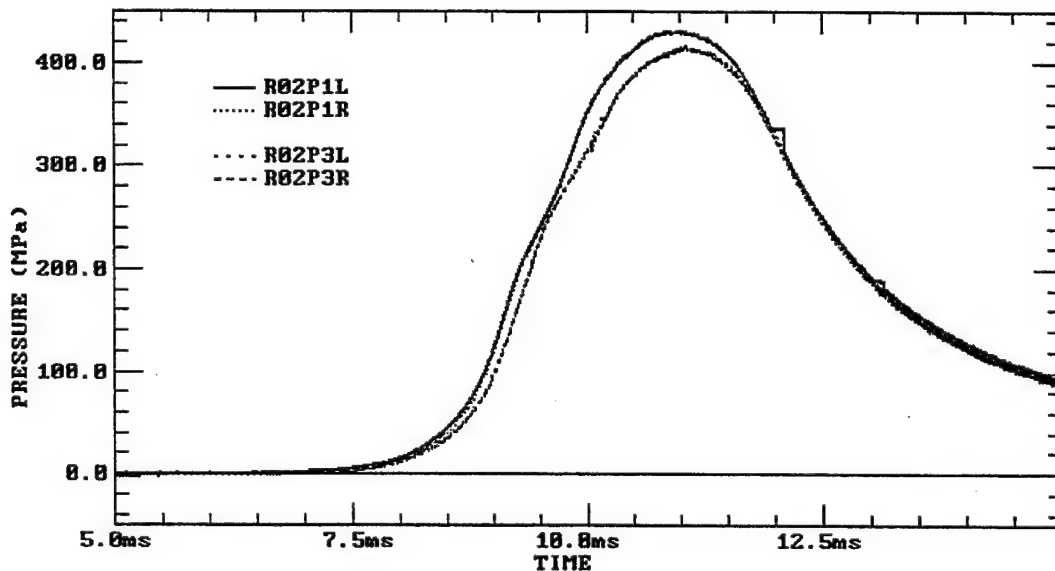


Figure 13. Combustion Chamber Pressure-time Data for Round 2.

Table 5. Combustion Chamber Pressure Data For Rounds 1-3.

	Gage Type	Filler Mat'l*	Round 1		Round 2		Round 3		Average	
			Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)
P1L	6211	1	425.5		430.6		425.1		427.1	
				-4.6 (1.1)		-1.4 (0.3)		-7.8 (1.8)		-4.6 (1.1)
P1R	6211	1	430.1		432.0		432.9		431.7	
P3L	6211	1	415.0		416.3		419.2		416.8	
				+3.4 (0.8)		+2.6 (0.6)		-0.6 (0.1)		+1.8 (0.4)
P3R	6211	1	411.6		413.7		419.8		415.0	

* see Table 3 for filling material

The next three series of firings were done to evaluate the other filling materials listed in Table 3.

Rounds 4-6 made use of 6211 pressure transducers in all four positions. Wolf's Head #2917 Grease was used in positions P1L, P1R, and P3R and the Dow Corning high vacuum grease was once again used in P3L. The results of these three tests are shown in Table 6. They again show a good comparison within the P1-plane between the level of the quasi-steady-state pressure when this grease is used (compare P1L to P1R). In addition, there does not appear to be any appreciable difference in the level of the quasi-steady-state pressure when comparing the Dow Corning high vacuum grease (P3L) and the Wolf's Head #2917 grease (P3R).

Table 6. Combustion Chamber Pressure Data For Rounds 4-6.

	Gage Type	Filler Mat'l*	Round 4		Round 5		Round 6		Average	
			Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)
P1L	6211	2	433.1		441.2		441.6		438.6	
				-5.5 (1.3)		-5.5 (1.2)		-6.3 (1.4)		-5.8 (1.3)
P1R	6211	2	438.6		446.7		447.9		444.4	
P3L	6211	1	420.7		429.9		430.5		427.0	
				-5.3 (1.2)		-1.2 (0.3)		-7.0 (1.6)		-4.5 (1.0)
P3R	6211	2	426.0		431.1		437.5		431.5	

* see Table 3 for filling material

Rounds 7-9 again made use of 6211 pressure transducers in all four positions. Pennzoil #705 multipurpose lubricant was used in positions P1L, P1R, and P3R and the Dow Corning high vacuum grease was once again used in P3L. The results of these three tests are shown in Table 7. They show a good comparison within the P1-plane between the level of the quasi-steady-state pressure when this grease is used (compare P1L to P1R). In addition, there does not appear to be any appreciable difference in the level of the quasi-steady-state pressure when comparing the Dow Corning high vacuum grease (P3L) and the Pennzoil #705 multipurpose lubricant (P3R).

Table 7. Combustion Chamber Pressure Data For Rounds 7-9.

	Gage Type	Filler Mat'l*	Round 7		Round 8		Round 9		Average	
			Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)
P1L	6211	3	442.4		434.6		449.1		442.0	
				-7.9 (1.8)		-3.9 (0.9)		-1.8 (0.4)		-4.6 (1.0)
P1R	6211	3	450.3		438.5		450.9		446.6	
P3L	6211	1	437.8		421.9		428.6		429.4	
				+2.4 (0.6)		-5.9 (1.4)		-6.1 (1.4)		-3.2 (0.7)
P3R	6211	3	435.4		427.8		434.7		432.6	

* see Table 3 for filling material

Rounds 10-12 again made use of 6211 pressure transducers in all four positions. Nonfluid Oil Corp. ZL2 multipurpose grease was used in positions P1L, P1R, and P3R and the Dow Corning high vacuum grease was once again used in P3L. The results of these three tests are shown in Table 8. They again show good comparison within the P1-plane between the level of the quasi-steady-state pressure when this grease is used (compare P1L to P1R). However, there does appear to be about a 3% difference (as compared to about 1% for previous filling materials) in the level of the quasi-steady-state pressure when comparing the Dow Corning high vacuum grease (P3L) and the Nonfluid Oil Corp. ZL2 multipurpose grease (P3R). Apparently, the properties of this grease are different enough from the others that a pressure difference can be detected. The exact properties of the ZL2 multipurpose grease were not available to the investigators.

Table 8. Combustion Chamber Pressure Data For Rounds 10-12.

	Gage Type	Filler Mat'l*	Round 10		Round 11		Round 12		Average	
			Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)
P1L	6211	4	459.2		450.8		457.5		455.0	
				+1.1 (0.2)		-1.4 (0.3)		No Data		-0.2 (0.0)
P1R	6211	4	458.1		452.2		No		455.2	
P3L	6211	1	431.8		426.6		432.8		430.4	
				-17.3 (3.8)		-10.2 (2.3)		-12.7 (2.9)		-13.4 (3.0)
P3R	6211	4	449.1		436.8		445.5		443.8	

* see Table 3 for filling material

4.5 Effects of Pressure Transducer Type on the Chamber Pressure Measurement. The final series was performed to evaluate the differences in two popular pressure transducers used in the large-caliber gun test business. Rounds 13-15, and 17 (in 16 there was a long ignition delay caused by the primer) made use of the Kistler 6211 piezoelectric pressure transducer (quartz) in P1L and P3R and the E30MA piezoelectric pressure transducer (Yuma Proving Ground, tourmaline) in P1R and P3L. Dow Corning high vacuum grease was used in P1L and P1R. Wolf's Head #2917 was used in P3L and P3R.

Figure 14 shows a plot of the pressure-time data for Round 13. As can be seen in the figure, there is an appreciable difference in the quasi-steady state pressures recorded in the same plane with different transducers. The results of these four tests can be seen in Table 9. The results show that the Kistler 6211 reads about a 5% higher quasi-steady-state pressure than the E30MA in both the forward and rear of the chamber. The question remains as to which gage is reading the more correct quasi-steady-state pressure level. This measurement discrepancy has been experienced by other investigators¹⁴⁻¹⁷ who have not been able to answer the question. In the 120-mm firings presented here, copper crusher gages were also used to measure the maximum chamber pressure. The chamber pressures read from these gages were always between the values given by the two piezoelectric gages. Typically, the Kistler 6211 read about 3% higher than the copper crushers and the E30MA read about 2 % lower than the copper crushers. The linearity of the two gages is approximately the same (+/-2%) and could be a possible cause for the discrepancy if one gage was high and the other low.

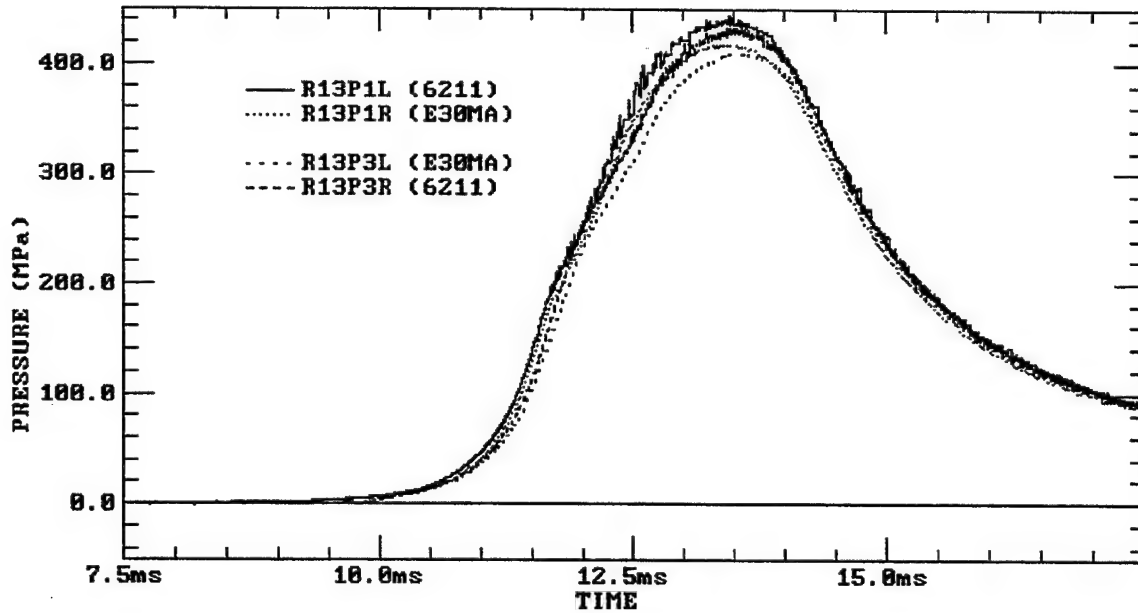


Figure 14. Combustion Chamber Pressure-time Data for Round 13.

Table 9. Combustion Chamber Pressure Data For Rounds 13-15, and 17.

	Gage Type	Filler Mat'l	Round 13		Round 14		Round 15		Round 17		Average	
			Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)	Pmax MPa	PL - PR MPa (%)
P1L	6211	1	444.0		449.2		441.1		433.3		441.9	
				+26 (5.9)		+22.7(5.1)		+19.6(4.4)		+19.0(4.4)		+21.8(4.9)
P1R	E30MA	1	418.0		426.5		421.5		414.3		420.1	
P3L	E30MA	2	409.4		416.3		409.7		407.3		410.7	
				-24.3 (5.6)		-22.6 (5.1)		-22.3 (5.2)		-19.2 (4.5)		-22.1 (5.1)
P3R	6211	2	433.7		438.9		432.0		426.5		432.8	

* see Table 3 for filling material

Based on the combustion chamber pressure data presented here, it appears that there is no appreciable difference in the Dow Corning High Vacuum Grease, the Wolf's Head #2917, and the Pennzoil #705 multipurpose lubricant at this pressure level. There was an indication that the Nonfluid Oil Corporation ZL2 multipurpose grease was responsible for a 3% increase in the measured quasi-steady-state pressure compared to the same measuring system with Dow Corning high vacuum grease. It was also determined that the Kistler 6211 pressure transducers read a quasi-steady-state pressure level 5% higher than the E30MAs. At this time, it is not known which gage reflected the more accurate pressure level. More tests are planned to further analyze other transducers in addition to those used in this study at these pressure levels as well as at higher pressure levels where other concerns are noted in the literature. 14-17

5.0 CONCLUSIONS

A series of tests was performed in a 120-mm cannon to characterize the effects of transducer type, transducer port configuration, thermal protection medium, and severe mechanical forces on the amplitude and frequency response of the pressure measurement. These tests demonstrated that the use of single-diameter pressure ports with cavity depths of 0.254 mm (0.010 in) and 0.711 mm (0.028 in) will more accurately characterize the oscillatory nature of the pressure measurement than would the use of a single-diameter port with a cavity depth of 1.600 mm (0.063 in). These data do not appear to tell us much information concerning the application of the simple organ pipe equation. However, they do support the theory that as the depth of the single-diameter cavity gets larger, the natural frequency of the cavity gets lower (not necessarily in proportion to $C_0/4l$).

Tests also demonstrated that thermal protective gage port filling material have a profound effect on the pressure measurement and appears to cause an earlier pressure rise than can be supported by projectile location determined by the microwave interferometer data. The filling material does not appear to have any effect on the magnitude of ringing seen on the down-bore pressure transducers after peak pressure. The Kistler 607C pressure transducers that were exposed to the very high-temperature combustion environment survived quite well. During testing, only one gage had to be replaced and that was due to a bad sealing surface on the gage. After firing, the gages were re-calibrated and demonstrated good linearity and repeatability.

A portion of the 120-mm test plan was designed to determine the effects of different filling materials and different transducers on the fidelity of the quasi-steady-state combustion chamber pressure measurement. These tests demonstrated that the quasi-steady-state pressure level in the chamber can be measured to an accuracy of about 1% within a given longitudinal location in the combustion chamber. This also implies that the gage calibration, gage linearity, mounting torque repeatability, and measurement process are good to about 1%. There does not appear to be any appreciable difference in the level of the quasi-steady-state pressure measurement when comparing the Dow Corning high vacuum grease, the Wolf's Head #2917 grease, and the Pennzoil #705 multipurpose lubricant. However, there does appear to be about a 3% difference (as compared to about 1% for previous filling materials) in the level of the quasi-steady-state pressure when comparing the Dow Corning high vacuum grease and the Nonfluid Oil Corporation ZL2 multipurpose grease. It was also shown that the Kistler 6211 pressure transducer (quartz) reads about 5% higher than the E30MA pressure transducer (tourmaline) in both the forward and rear of the chamber. On average, the Kistler 6211 read about 3% higher

than the copper crusher gages and the E30MA read about 2 % lower than the copper crusher gages. The discrepancy is clear, but since the number of tests was small, no conclusion can be reached as to which gage gives the most correct quasi-steady-state pressure level.

The results of these tests have established this test configuration as a viable diagnostic tool that can be used for future pressure measurement phenomenology studies. More research is planned to further evaluate the use of single-diameter pressure ports to characterize the oscillatory portion of the pressure measurement. In addition, tests are planned to further analyze other transducer types in addition to those used in this study at these pressure levels; as well as at higher pressure levels, where other concerns are noted in the literature.¹⁴⁻¹⁷

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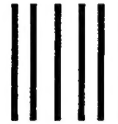
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